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IMPROVING THE DESIGN OF DIAMOND WHEEL FOR HIGH-SPEED GRINDING

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ABSTRACT

Grinding at high speeds is a complex process requiring specific tools for successful use. Rotational stresses during high-speed grinding can lead to failure if the wheel is not correctly designed. These results are extremely difficult to be obtained during a large number of field experiments due to the high cost of testing equipment. So, the article describes ways of improving the integrity of the body of the diamond grinding wheel for high-speed regimes using analytical approaches and finite element method.

Keywords: high-speed grinding, finite element method, destructive stress, design, construction

1. INTRODUCTION

Currently, one of the most promising ways of increasing the efficiency of grinding operations and expand its technological capabilities is to increase the cutting speed, defined by the rotation frequency of the wheel. By increasing the peripheral speed of the grinding wheel, the wear reduction of its working surface as well as the cutting forces are determined, whilst the quality of the machined surface is improved [1-4]. High-speed processing modes require appropriate equipment with the corresponding spindles, grinding tools, subsystems and rigidity. The cost of the tool is still the main limitation for the wider use of the diamond grinding, as well as the need for a better understanding and monitoring the grinding process [2, 5, 6]. To achieve higher speeds an understanding of how wheels fail is required. Vitrified bonds are brittle. Plastic materials will fail catastrophically, when the localized stresses exceed the material strength. Stresses occur from clamping of the wheel, grinding forces,

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acceleration and deceleration forces on starting, stopping, or changing speed, wheel unbalance, or thermal stresses. However, under normal and proper handling and use of the wheel, the greatest factor is the centrifugal stresses due to the constant rotation at operating speed.

For diamond wheels working at high speeds, it is necessary to consider not only the performance, but also the safety of the tool under these conditions. For designing the wheel, it is necessary to solve the following problems: the choice of the material and the design of the wheel body, the method of adhesion of the diamond layer and the body of the wheel.

For the high-speed grinding wheel body the selected material should have a high stiffness coefficient. These criteria, for example, correspond to aluminum alloys, titanium alloys, plastics reinforced with carbon fibers (CFRP). Since the displacement (deformation) and stresses can be reduced by a combination of the best materials and using, for example, nanostructured additives, the rigidity can be very high, as shown in Eqns. (1) and (2):

$$\sigma_{max} = \frac{1}{4}\{(3 + \vartheta) + \frac{(1-\vartheta)}{k^2}\}\frac{\rho R^2 \omega^2}{g}) \quad (1)$$

$$U = \frac{1}{4}E\{(3 + \vartheta) + \frac{(1-\vartheta)}{k^2}\}\frac{\rho R^2 \omega^2}{g}, \quad (2)$$

where: E – Young’s modulus; ϑ – Poisson’s ratio; ρ - specific density; ω - angular velocity; k - $\frac{R}{r}$; R – external diameter; r – internal diameter; g – acceleration of gravity.

In addition, it is necessary to take into account the ease of obtaining the selected material. Note that, at peripheral speeds of 200 m/s titanium and aluminium alloys are used, whilst steel is used at a peripheral speed of 160 m/s. Furthermore, recently, considerable attention is paid to the processes of recycling and re-use of these materials to protect the environment.

Question of achieving high cutting speed during grinding or sharpening, is a matter of selecting the ratio vs diameter of the grinding wheel and the spindle speed. On one hand, there are difficulties of achieving maximum spindle speed and, on the other hand, manufacturing expediency of the large diameter of the wheel. This dilemma is difficult enough to be solved, but the analysis of the factors makes it possible to draw some conclusions, namely: the greater is the diameter of the wheel, the greater is the number of cutting elements which can be placed on it and the higher the resistance, but the greater mass results in beating the system.

At high rotational speed range, the wheel edge must perform movement in a plane, but it will retain only the inertial forces which may be, and usually are, very harmful in case of vibrations. This freedom will lead to dangerous vibrations. Moreover, there is possibility of precise manufacturing process and balancing of the grinding wheel in the diameter range of 300 mm [5, 6]. This diameter allows for achieving cutting speeds up to 200-400 m/s with a frequency of 20000-40000 rev/min. Analysis of the grinding wheel sizes used for grinding tools indicates that the most common diameters range from 125 to 250 mm. This is determined by the configuration of sharpened tools, which constitutes the major factor in this case.

It may be noted that, manufacturing a solid wheel with good cutting properties and the strength of steel may be not possible in the near future [1-6]. Therefore, out of this contradiction is the development of modular design. The disadvantage of the assembly is a discontinuous surface of the working layer. Therefore, in this study attention is directed towards the development of the design of the grinding wheel based on a durable material and diamond layer in the form of a ring. Furthermore, the choice of its shape is also very important for wheels used in high-speed grinding. The development of the design finite element method (FEM) allows for predicting and reducing the stress and displacement (deformation), arising due to the centrifugal force. In particular, the displacement under the action of centrifugal forces is directly related to the destruction of the wheel. Monitoring these stresses is the key to the development of the design.

To achieve a high cutting speed due to the use of wheels with a diameter of more than 1000 mm on the existing equipment is practically not possible, although the frequency of 10000 r/min does not seem large, but it will require bearings with a diameter of more than 200 mm with the value of runout of no more than 0.1 mm. The engine will require at least 20 kW, equipped with balance and precision bearings, which will be very difficult and expensive. Therefore, there is no need of improving the tool diameter and the driving power.

Literature review indicates that, in modern equipment for high-speed machining, spindles are used to up-belt drive from an asynchronous motor and synchronous motors with frequency of rotation of the drive shaft up to 40000 rev/min. Electric motors are usually regulated by frequency regulators allowing for smooth acceleration, as well as equipped with high-speed bearings. At the same time, hydrodynamic bearings are used for hydrostatic and precision ball bearing [1, 7].

Question of development of promising variants of diamond wheels for high-speed regimes at the moment is still open. Therefore, the development of a 3D modelling methodology for predicting the behavior of the tool at all major phases of its life cycle is one of the least expensive ways to increase its efficiency and, hence, the efficiency of the treatment process. In this study examined is the 3D modeling of industrial strength tests of diamond wheels undergoing stresses arising in the processing of high-speed grinding [7-10]. Model experiments in this case, make it possible to establish the dependence between the integrity of wheels and a wide range of materials and design of the tool [11].

2. Design of High-Speed Wheels

Based on the analysis of the literature, several basic ways to strengthen the structure of the diamond wheel, designed for high-speed conditions, can be defined, see Figure 1.

As shown in Figure 1, grinding wheel design provides a theoretical possibility of treatment at a cutting speed of up to 130 m/s [1-3, 7]. Another factor limiting the increase of the grinding speed is the insufficient strength of grinding wheels. The analysis of existing designs of grinding wheels for processing at speeds up to 100 m/s revealed three fundamentally different designs:

1. Work layer, reinforced with a steel or plastic mesh.
2. The metal case which is fixed (usually by adhesive) diamond layer.
3. Followed sector type with mechanical fastening and diamond abrasive elements of special form.

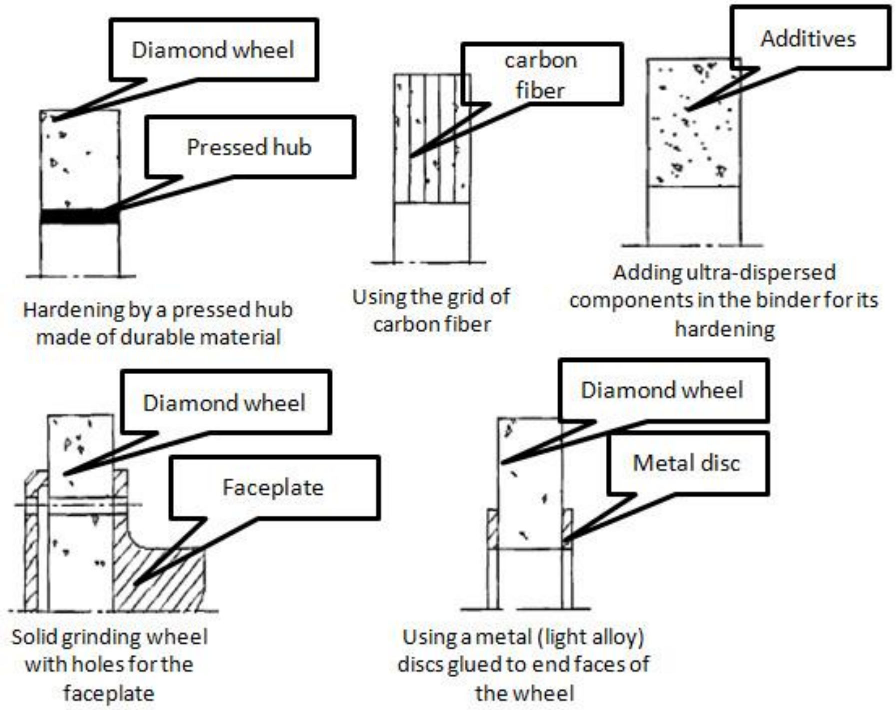

Figure 1. Methods of modifications in construction of the diamond wheel for high-speed processing.

Imbalance of the wheel is caused by vibration due to centrifugal force, worsening as the shape and surface roughness increase. Balance must be checked before the starting of the high-speed grinding, because imbalance can arise from error in the fitting with the spindle or an inaccuracy in the body shape. The disadvantage of these modifications of diamond wheels, see Figure 1, is a significant complication of the construction. Additional elements in the construction of the wheel may increase the entire grinding system imbalance. Current researches are based on the modernization and strengthening of the existing diamond wheels, see Figs. 1 and 2. However, it should be pointed out that grinding at high speeds is a brand new process, which requires a new high-tech tool that would solve all issues of safety, stability and cost.

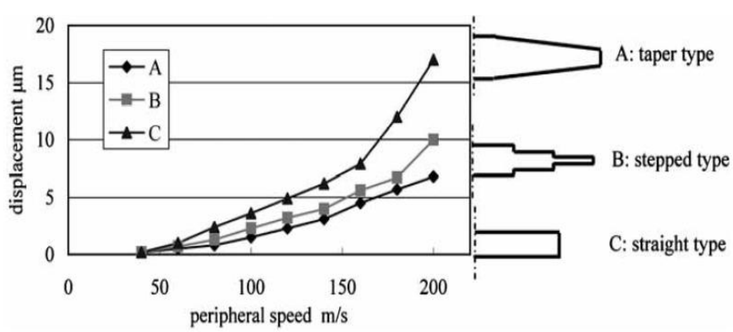

Figure 2. Dependence strain vs peripheral speed (with different shape of the wheel body) [7].

In Figure 2 the dependence strain vs peripheral speed for different shapes of the body of the wheel is presented. The most important part is to restrain the imbalance of the wheel and, therefore, a balance modification mechanism must be equipped even on the machine side; this is required for the adjustment of the balance to become possible on the machine. Although a balance modification mechanism that use the liquid is general, it is not sufficient when a wheel is rotating at high speed, since the liquid leans to the outside due to the centrifugal force. After the wheel is installed on the machine, it is made most effective by the operator adding weight for adjustment. However, this method cannot be recommended from the viewpoint of safety [1, 5-8]. Therefore, the challenge to reduce the strain in the diamond wheel during high-speed grinding constitutes a major aspect towards expanding the technological features of this process. This problem should be solved in order to increase the use of high-speed grinding.

3. Numerical Simulation of the Diamond Wheel Strength

In order to improve the reliability of construction components and machine parts, significant design decisions have to be taken, because the structure must be strong enough, and, if necessary, rigid and stable, whilst, at the same time, the lowest consumption of materials, complexity and cost of manufacturing have to be obtained.

To a large extent, this problem can be solved by rational design based on modern methods of strength calculations. It must be assumed that the highest stress in the cross-section of the designed element at a certain load lies below the limit of the stress at which there is a risk of plastic deformation or fracture. In this case, the development of wheel design method of calculation turbine blades for strength and finite element method (FEM) are used, in order to predict and reduce the stress and displacement (deformation) arising due to centrifugal forces. In particular, the displacements under the action of centrifugal force are directly related to the destruction of the wheel and influence the quality of grinding.

The criteria for evaluating the wheel design are the safety factors of the various parameters, determining the strength, deformability, load bearing capacity and durability of the wheel. Calculations should be based on an accurate assessment of stresses and strains, given stress concentration, knowledge of the material in the same conditions of loading and use of modern ideas about the accumulation of damage [12-14].

In the design of grinding wheels, disks of considerable thickness commensurable with the radius are used. In this case, the methods of calculation, using flat tension conditions and normal strain hypotheses are not suitable. Calculation of the spatial stress state is made possible by the development of finite element method (FEM), which allows for the implementation of well-designed elastic-plastic problem solving procedures and computers with sufficiently large efficiency, as well as by using analytical methods for the calculation of turbine blades that operate in similar conditions.

A general scheme for the optimal design of the disc is shown in Figure 3. The basis of the algorithm is derived from the design of turbine blades [15]. The algorithm is improved by a combination of the analytical method and finite element analysis. The content of each block depends on the design goals and level.

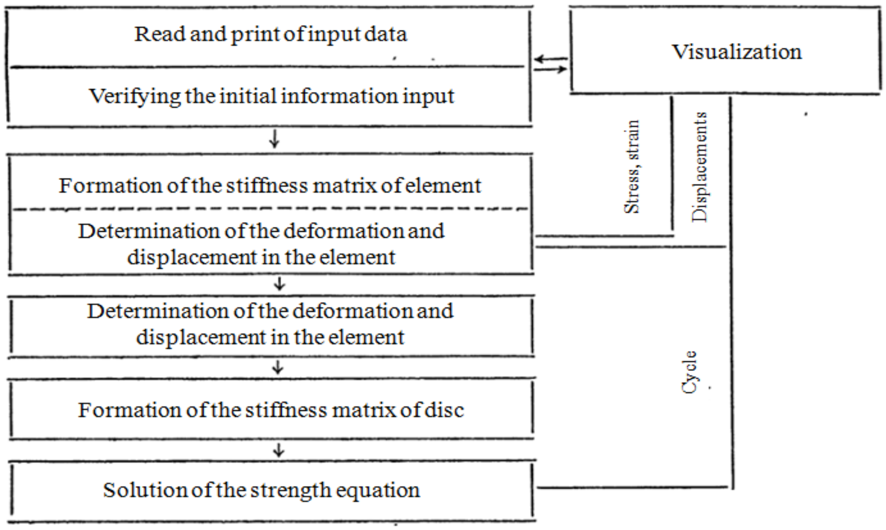

Figure 3. General algorithm of calculating the base of diamond wheel for high-speed grinding.

By ignoring the thermal deformation and using the results of [15], the differential equation of the disk tension is obtained:

$$\frac{d^2U}{dr^2} + \frac{d}{dr}\left(\ln\frac{rhE}{1-\mu^2}\right)\frac{dU}{dr} + \left[\frac{\mu}{r}\frac{d}{dr}\left(\ln\frac{rhE}{1-\mu^2}\right) + \frac{d}{dr}\left(\frac{\mu}{r}\right) - \frac{1}{r^2}\right]U = -\frac{r\mu^2}{E}g_r, \tag{3}$$

where: U=u(r) – displacement of cross sections of the disc; h=h(r) – disc thickness; E, μ - Elastic modulus and Poisson's ratio of the disc material; gr=ρω2r – volume loading caused by centrifugal force; ρ – material density; ω – angular velocity (rad/sec).

The boundary conditions that represent the method of attaching the edges of the disk, i.e., r = a and r = b, are shown in Figure 4. For the grinding wheel body, freely planted on the shaft and not interacting with the treated surface, the boundary conditions are:

$$\sigma_{rr}|_{r=a} = 0 \text{ и } \sigma_{rr}|_{r=b} = 0, \tag{4}$$

where: σ_{rr} - radial stress, see Fig. 4.

Taking into account that,

$$\sigma_{rr} = \frac{E}{r\mu^2}\left(\frac{dU}{dr} + \mu\frac{U}{r}\right) \tag{5}$$

results in:

$$\left.\frac{dU}{dr}\right|_{r=a} + \mu\frac{U|_{r=a}}{a} = 0 \text{ и } \left.\frac{dU}{dr}\right|_{r=b} + \mu\frac{U|_{r=b}}{b} = 0 \tag{6}$$

The algorithm for calculating the turbine blades allows to define the profile of a rotating disc, in which the stresses will be the same in all of its cross sections. Note that, the tension will be minimal depending on the chosen material. Therefore the grinding wheel will be less deformed at high processing speeds.

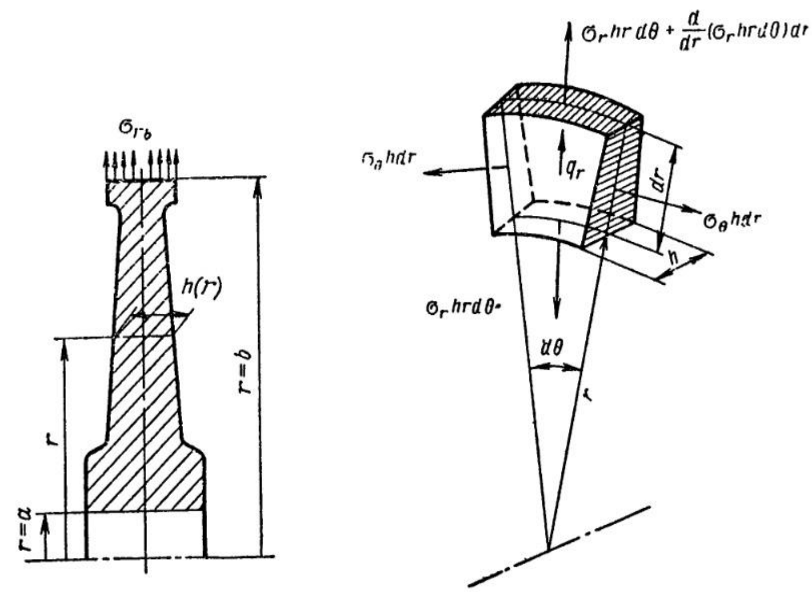

Figure 4. Boundary conditions of attaching the edges of the disk.

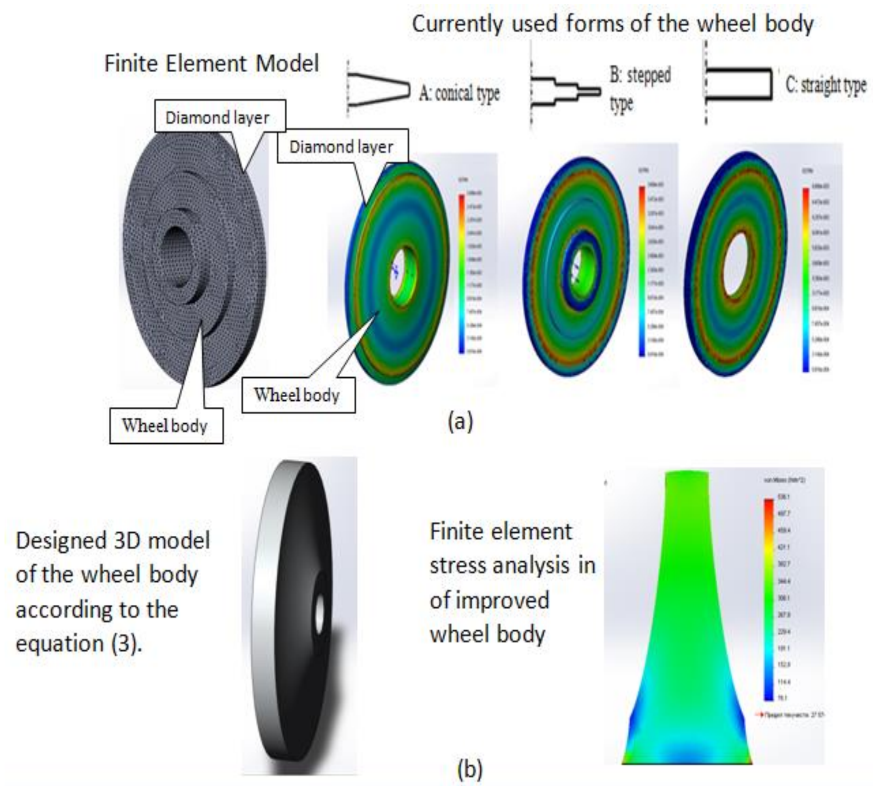

Figure 5. (a) Distribution of deformations in the wheel components during the action of centrifugal forces at high-speed grinding at peripheral speed of 150 m/s (Wheel body material: light aluminum alloy; diamond layer-iron based binder) (b) 3D model according to Eq. (3) and FEM simulation of improved wheel body.

For the known designs a series of calculations were carried out in order to compare experimental data with modelling, see Figure 5(a). The results of these calculations are confirmed by studies [7, 14] carried out with the help of a high-speed spindle, which allows a peripheral speed of 500 m/s for wheels with a diameter of 200 mm. Correlation of results of FEM calculations and experiments, see Figure 2(a), in the range of rotational speeds range from 50 to 200 m/s, is 5-8%. That indicates the adequacy of modeling and its use to predict the behavior of the wheel during processing.

Rotational stresses during high-speed grinding can lead to failure, if the wheel is not correctly designed. The use of FEM analysis for the design of the wheel and the number of segments, in the case of super-abrasive wheels [16], plus the improved performance of modern machines, has reduced the risk of failure due to incorrect wheel design. The employed algorithm for calculating the turbine blades allowed for defining the profile of a rotating disc, in which the stresses are the same in all of its cross sections, see Figure 4(b). Note that, the greatest strain value in this case is 0.34 µm, thus, the deformation is less than when using the known form of the wheel body [11]. A study shows that the optimization of the wheel shape in the future will lead to a strain decrease on the action of centrifugal forces by 10-15%.

Safety for diamond wheels at high speeds is one of the most important problems of their operation. Using the algorithm, a hyperbolic shape of the diamond wheel body, in which stresses in all sections remain constant, has been obtained, see Figure 5(b). To check the safety of the structure in comparison with the existing one, see Figure 5(a), distributions of the safety factor were predicted, as indicated in Figure 6.

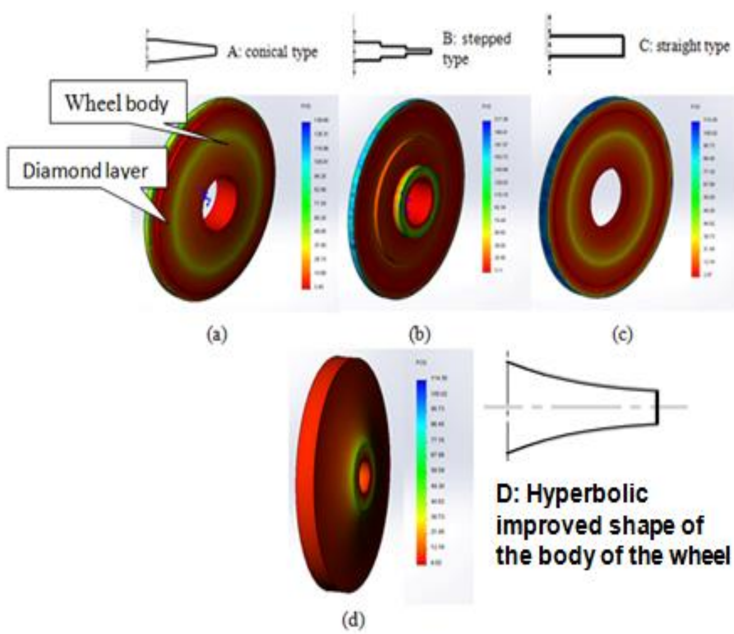

Figure 6. Distribution of the minimum safety factor depending on the wheel design for a peripheral speed of 300 m/s: (a) 3.45; (b) 3.11; (c) 2.61; (d) 4.05 (Wheel body material: light aluminum alloy; diamond layer-iron based binder) (Red color indicates the places of distribution of the largest value of the safety factor).

For plastic materials of the wheel body, the tensile and compressive stress limit is the yield strength of the material. In this case, the respective stress is obtained from the yield strength as:

$$[\sigma] = \frac{\sigma_T}{n} \quad (7)$$

where: σ_T - yield strength of the material; n - safety factor.

For brittle materials, the allowed tensile stress, $[\sigma_t]$ and the related compressive stress $[\sigma_c]$ are obtained, based on the ultimate strength $[\sigma_{tu}]$ and $[\sigma_{cu}]$:

$$[\sigma_t] = \frac{\sigma_{tu}}{n} \, and \, [\sigma_c] = \frac{\sigma_{cu}}{n} \quad (8)$$

Safety factors with respect to temporary resistance in brittle strength during dynamic action should be chosen quite large. This is due to the fact that even a single excess of the maximum ultimate stress causes destruction.

The safety factor is calculated using the finite element method on the maximum normal stresses, see Figure 5:

$$\frac{\sigma_{norm}}{\sigma_{ultimate}} < 1 \quad (9)$$

σ_{norm} - value of the maximum normal stress; $\sigma_{ultimate}$ - value of ultimate stresses for the materials of the system

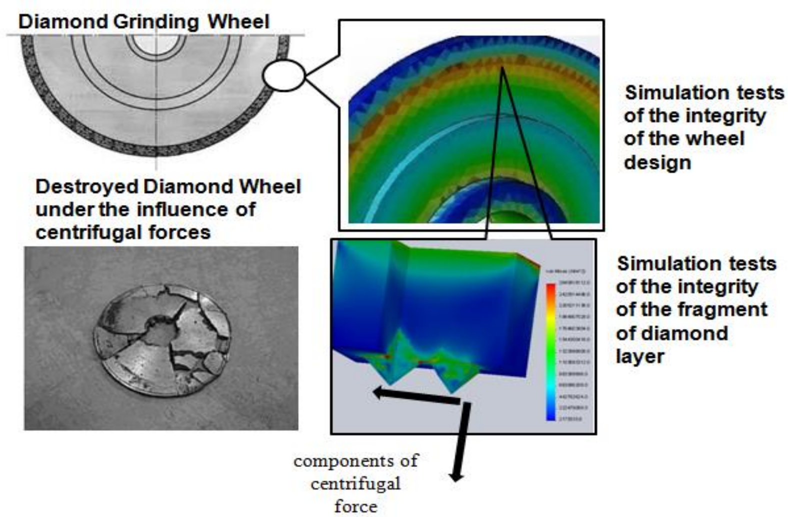

Figure 7. Concept of 3D modeling of structural integrity of the fixing diamond layer to grinding wheel. Simulation of the integrity of the fixing diamond layer to the base circle.

Another problem when using high-speed grinding is the destruction of the fixing diamond layer. In this case, a variety of mechanical fasteners is used, see Figure 1, but such attachments complicate the design and may contribute to a misbalance of the wheel operating at high speeds. Therefore, the task is directed towards improving the fixing of the diamond layer to the body of the wheel. This paper considers the improvement of the known method of fastening of the diamond layer by bonding together it with the body of the wheel, see Figure 7.

To improve the fixing of the diamond layer on the body, holes along the external diameter of the wheel are made, see Figure 8. The Finite element model and the boundary conditions for the simulation of the stresses arising at high processing speeds for this case are also presented in the same Figure.

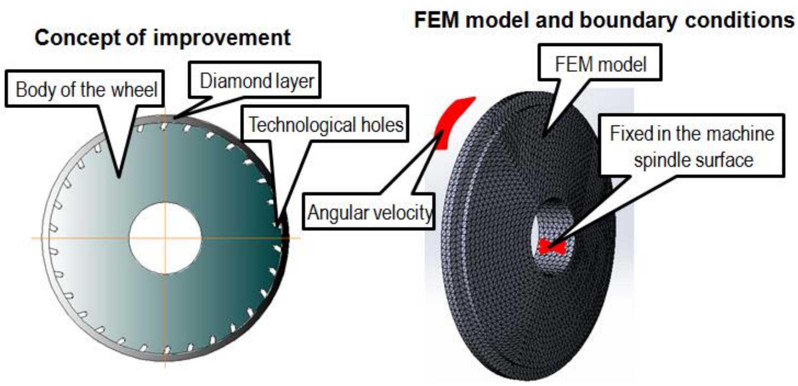

Figure 8. Improving the fixing conditions of the diamond layer for wheels operating at high speeds.

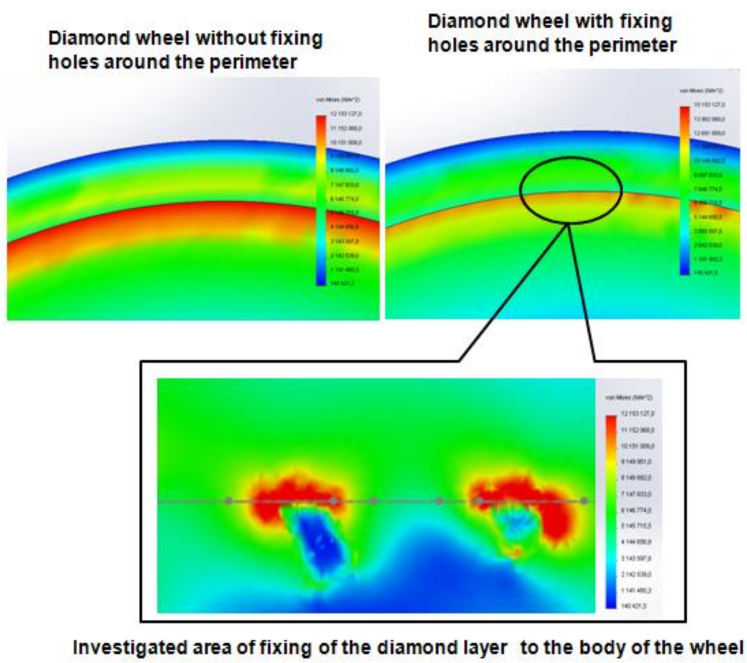

Figure 9. Distribution of stresses in the fixing zone of the diamond layer.

In Figure 9 the distribution of stresses in the fixing zone of the diamond layer to the wheel body is presented. The fastening holes on the external perimeter of the body of the wheel lead to a significant stress reduction in this regime, due to the increase of the contact area in place of adhesion of the diamond layer. Also, by drilling fixing holes at an angle of 30 degrees in the direction of the wheel rotation, the possibility of appearance of destructive stress concentrators in the mounting area of the diamond layer is reduced.

CONCLUSION

Summarizing the main simulation results pertaining to the optimisation of the design of the diamond wheel body used in high-speed grinding the following concluding remarks may be drawn:

1. A 3D methodology for determining the strength characteristics of diamond wheels for high-speed grinding was developed.
2. Diagrams of the distribution of stresses for a variety of materials, as well as test modes and design of the wheel were obtained by calculations.
3. The algorithm for calculating the turbine blades allows for defining the profile of a rotating disc, in which the stresses will be the same and minimum in all of its cross sections. Tension will be minimal depending on the chosen material.
4. Simulation indicates the feasibility of using fixing holes on the external perimeter of the body of the wheel to reduce the stresses in this area.

REFERENCES

[1] Klocke F., Brinksmeier E., Evans C., Howes T., Inasaki I., Tonshoff H., Webster J. A. and D. Stuff (1997) High Speed Grinding - Fundamentals and State of Art in Europe, Japan and the USA. *Annals of the CIRP*. 46/2:715-724.

[2] Kramer, D., Rehsteiner, F., and Schumacher, B., 1999, ECD, a New Method for Grinding of Modern High Performance Cutting Materials to Highest Quality, *Annals of theCIRP*, 48/1:265-268.

[3] Starkov V. K. (2002) New generation of high-porous abrasive tool, ISN 0042-4633 Vestnik *Maschinostroenia*, No. 4, 56-62.

[4] Wang C. Y., Hu Y. N., Ding H. N.. Cutting Forces in Sawing Process of Reinforced Concrete. Materials Science Forum; 2004, 471-472: p292-297.

[5] Kovac, et al. (1993) A Feasibility Investigation of High-speed Low Damage Grinding of Advanced Ceramics, Proc. of the %th Int. Grinding Conference, SME, Ohio.

[6] Salmon S. C. (1992) Modern Grinding Process Technology, McGraw-Hill, Inc.

[7] Webster J, Tricard M. (2004) Innovations in Abrasive Products for Precision Grinding. Annals of the CIRP. 53/2: 597–617.

[8] Uhlmann E., Hochschild L. (2013) Tool optimization for high speed grinding. *Production Engineering*. 7: 185-193.

[9] Hwang T. W., Evans C. J., Malkin S. (2000) An Investigation of High Speed Grinding with Electroplated Diamond Wheels. *Annals of the CIRP*. 49/1: 245-248.

[10] Shi Z. and Malkin S. (2003) Investigation of Grinding with Electroplated CBN Wheels. *Annals of the CIRP*. 53/1: 267 – 270.
[11] Funayama N. and Matsuda J. (2005) Development of High-Performance cBN and Diamond Grinding Wheels for High-Speed Grinding, New Diamond and Frontier Carbon Technology. 15/4, MYU Tokyo.
[12] Jackson M. J., Barlow N., and Hon K. K. B., Computer Aided Design of High-Performance Grinding Tools, Proceedings of the Institution of Mechanical Engineers (London), *Part B - Journal of Engineering Manufacture*, (2001), 215, 583-588. ISSN 0954-4054.
[13] Syoji K., Yamazaki N., Watanabe R. and Kuriyagawa T., Influence of Wheel Surface Speed on Grindability of Grinding Material - Studies on Ultra-High Speed Grinding（3rd Report, J of JSPE (Japan Society of Precision Engineering), 66, 7 (2000), 1145-1149.
[14] Marinescu I., Hitchiner M., Uhlmann E. (2006) *Handbook of Machining with Grinding Wheels.* Manufacturing Engineering and Materials Processing. CRC Press.
[15] Demyanushko I. V., Birger I. A. (1978) Calculation of rotating disks. ”Engineering”, Moscow, *Engineering.* 248 p.
[16] Brinksmeier E., Aurich J. C., Govekar E. (2006) Advances in Modeling and Simulation of Grinding Processes*. Annals of the CIRP*. 57: 667-696.